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14. ABSTRACT
In this project, we develop an ensemble tropical cyclone (TC) genesis forecast model based on multiple data sources including NOGAPS, NCEP and ECMWF global model output for the period of 2004-2012. A nonlinear regression formulation is used to combine optimal key meteorological variables that control TC formation. The constructed TC genesis forecast model is implemented and tested at Joint Typhoon Warning Center (JTWC).

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ENSEMBLE PREDICTION OF TROPICAL CYCLONE GENESIS

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OBJECTIVE AND RESEARCH TASKS

The objective of this project is to construct a short-term ensemble tropical cyclone (TC) genesis forecast model based on the analysis data of various operational models and to investigate TC genesis dynamics and its interaction with environmental flow. Predicting tropical cyclogenesis is one of the most challenging tasks in numerical weather prediction (Gray 1968, 1992; Fu et al. 2007). DoD Joint Typhoon Warning Center (JTWC) is in urgent need in developing an operational TC genesis forecast model. Recent studies show that numerical models with grid size near 10 km and explicitly resolved cloud schemes are required to have the potential to simulate the emergent evolution of TC precursors and predict the occurrence of TC genesis events (Jin et al. 2008). Tropical disturbances that serve as TC precursors exist all the time, but only a small percentage of them became TCs. In our previous NOGAPS 2004-2008 data analysis (Peng et al. 2012, Fu et al. 2012), we identified various key parameters that control cyclogenesis in the western North Pacific (WNP) and the tropical North Atlantic (NATL).

In the proposed research, we plan to develop an ensemble TC genesis forecast model based on multiple data sources (including NOGAPS, NCEP and ECMWF global model output for the period of 2004-2012) and multiple regression models with different predictors. The selection of key predictors will base on a box-difference index (BDI) methodology developed recently by us (Peng et al. 2012). The BDI approach is able to distinguish developing and non-developing disturbances in the tropics. A nonlinear regression formulation will be used to combine optimal key meteorological variables that control TC formation. Basin-dependent relationships between large-scale forcing and TC genesis require that separate formulations be constructed for different basins. And Bayesian Information Criterion (BIC) will be used to select a few better prediction models that derived from each dataset for both WNP and NATL. Finally, an ensemble model will be obtained that combine all these optimal models. The constructed new TC genesis forecast model will be implemented and tested at JTWC.

For understanding the synoptic and dynamic aspects of cyclogenesis, a multi-nested WRF model (with 2 km resolution in the innermost mesh) will be used to simulate both idealized and real-case cyclogenesis events. Through the diagnosis of the model outputs, we intend to understand the common and different development characteristics associated with cyclogenesis in an environment with a near bottom vortex (EBV) and an environment with a mid-level vortex (EMV). The genesis time for each model run will be defined based on an objective way. A concept of the cyclogenesis efficiency (which is related to the initial environmental dynamic and thermodynamic conditions) will be introduced. A number of idealized experiments will be designed to illustrate the relative importance of initial column-integrated absolute vorticity, PBL parameters, surface fluxes, and vertically integrated relative humidity in determining the TC genesis efficiency.

For understanding the climatic aspect of cyclogenesis, various statistical tools such as the wavenumber-frequency analysis, lagged regression analysis, and composite

analysis methods will be applied to understand the role of the MJO and ENSO in determining the intraseasonal and interannual variability of TC activity in the WNP.

MAJOR RESULTS

1. A Logistic Regression model for Tropical Cyclone Genesis Forecast

A nonlinear logistic regression formula is used to construct prediction models for 24-72 hours Tropical Cyclone (TC) genesis forecast in the western North Pacific (WNP). The predictors are selected based on Box Difference Index (BDI) that was introduced in previous studies (Peng et al. 2012; Fu et al. 2012). The selected predictors are further filtered by Bayesian Information Criterion (BIC) to obtain prediction models which have optimal combinations of predictors. The prediction models are trained using samples from year 2004-2008. The resulted models are used to hindcast 2009-2012 WNP TC genesis events. Two versions of the model (MODEL12 and MODEL13) are discussed in this paper. For 24-48 hour hindcast, MODEL12/MODEL13 shows a hit rate of 66%/72% and a false alarm rate of 23%/18%. For 48-72 hour hindcast, MODEL12/MODEL13 shows a hit rate of 86%/74% and a false alarm rate of 56%/50%. These two versions of model are also evaluated by JTWC for 2013 summer season. It shows MODEL13 has better Probability of Detection (POD) while MODEL12 has better False Alarm Rate (FAR). The models could become an important addition to the TC genesis forecasters' prediction toolset.

2. Tropical cyclone genesis efficiency: Mid-level versus bottom vortex

Cloud resolving WRF model is used to investigate the tropical cyclone genesis efficiency in an environment with a near bottom vortex or an environment with a mid-level vortex. Five experiments were designed with different initial vertical vorticity and moisture profiles. In the first experiment (MID_VORTEX), we mimic a mid-level precursor condition, by specifying an initial cyclonic vortex that has a maximum vorticity at 600 hPa and corresponds to a maximum wind speed of 8 m s^{-1} at a radius of 100 km and a size of 500 km radius where the wind vanishes. The vorticity gradually decreases both upward and downward, and vanishes at the surface. In the second experiment (BTM_VORTEX), an initial maximum precursor perturbation with a maximum wind speed of 8 ms^{-1} is located at the surface. The third and the fourth experiment contain a shallow mid-level vortex (SHAL_MID) and a shallow bottom vortex (SHAL_BTM), respectively, to identify the PBL effects and to better separate the mid-level and bottom vortices. The fifth experiment (MOIST) has the vortex profile

as the MID_VORTEX except with a greater moisture to investigate the dependence of TC genesis efficiency on the humidity profile.

All experiments above are able to develop a realistic and similar tropical cyclone, although the time taken is different. These time differences represent the genesis efficiency of the initial setup of the precursor vortex or the environmental moisture profile. It is found that all experiments share the following development characteristics: 1) a transition from non-organized cumulus-scale (~5 km) convective cells into an organized meso-vortex-scale (~50 km) system through upscale cascade and system scale intensification (SSI) processes, 2) the establishment of a nearly saturated air column prior to a rapid drop of the central minimum pressure, and 3) a convective-stratiform phase transition.

The numerical experiments above show that the genesis timing depends crucially on the initial vertical moisture and vorticity profiles. Based on these experiments and following the formula of the genesis potential index by Emanuel and Nolan (2004), we introduce a genesis efficiency index (GEI) to quantify the impact of initial vorticity and moisture profiles on the cyclogenesis. The key parameters in the GEI include the column integrated (1000-200hPa) absolute vorticity, relative vorticity at top of the planetary boundary layer (PBL), and vertically integrated (1000-500hPa) relative humidity (RH). With a similar column integrated (1000-200hPa) absolute vorticity, a bottom precursor vortex has a higher genesis efficiency than a mid-level vortex.

A salient feature among all five experiments above is a close relationship between the deepening of a moist layer and cyclogenesis time. For instance, in MID_VORTEX, there is a steady increase of the moist layer in the core region during hour 24-60. The 90% RH layer thickens from 900 hPa at hour 24 to about 500 hPa at hour 60. It is the establishment of this near-saturation air column that signifies the next development stage: deepening of cyclonic vorticity and a rapid drop of minimum sea level pressure. In all five experiments above, the genesis time occurs shortly after a near-saturated air column is set up. This preconditioning of the deep moist layer in the core region was also found in Nolan (2007) with different model physics. In all five experiments, the genesis start shortly after the column averaged RH reaching 90%, confirming that the establishment of a near-saturated deep air column is indeed a precondition for cyclogenesis.

3. Effects of vertical shears and mid-level dry air on tropical cyclone developments

A set of idealized experiments using WRF are designed to investigate the impacts of mid-level dry air layer, a vertical shear, and their combined effects, on tropical cyclone

(TC) developments. We design the following numerical experiments. In the control experiment (NOSH_CTL), we exclude both the dry air intrusion and the vertical shear. The initial fields contain a weak symmetric cyclonic vortex, with a maximum surface wind speed of 8 ms^{-1} at a radius of 150 km and the wind speed decreasing with height. This control experiment represents TC development under the favorable conditions with no vertical shear or a dry air layer. The second experiment (NOSH_DRY) is designed to examine the impact of the mid-level dry air layer with no mean flow. The specification of dry air layer follows Braun et al. (2012). A dry air layer is specified between 850 and 650 hPa, in which RH is set as 25% to mimic the dry SAL. This dry air layer is embedded at all grid points 150-km north of the initial vortex center. Four additional experiments with different vertical shears are designed. WSH_CTL and ESH_CTL are to examine the impact of different vertical shear profiles on TC development without mid-level dry air layer. In the flow with an easterly (westerly) wind shear, the zonal wind decreases (increases) linearly from 4 (-4 ms^{-1}) at the surface to -4 (4ms^{-1}) at the top of the model, and zero wind speed at 500 hPa. WSH_DRY and ESH_DRY have the same shear as in WSH_CTL and ESH_CTL, but with dry air located to the north of the vortex.

Numerical simulations show that without the existence of a mid-level dry air, the easterly and westerly shear effects on a TC development are quite similar. However, in the presence of dry air, the intensification rate and the final TC state in WSH_DRY and ESH_DRY are very different from each other. In ESH_DRY, dry air is quickly wrapped into the vortex core region during the first 48 hours, and covers almost the entire core region by 96 hour. As a consequence, there is no TC genesis. In contrast, in WSH_DRY, a TC is able to form, even though its intensification rate is weaker than that in WSH_CTL. The results indicate that the mid-level dry air imposed is very effective in hindering the storm development under the shear condition. The impact of dry air is highly sensitive to the orientation of vertical shear.

Why does the dry air allow the TC development under the westerly shear but not the easterly shear? We hypothesize that the difference is attributed to the relative location of dry air in relevance to the downshear quadrant. When it is placed to the right (left) of the downshear region, the dry air is easier (not easier) to be advected into the convective region of the FSC. Figure 8 contains two schematic diagrams showing how the westerly and easterly shear affect the FSC and the subsequent vertical alignment process in the case when the dry air is placed initially to the north of the vortex center. In the westerly shear case (Fig. 1a), a cyclonic vortex that is initially vertically aligned will gradually tilt eastward with height due to vorticity advection. While the upper-level vortex shifts eastward from the original position, the lower-level vortex shifts westward. According to the omega equation, positive (negative) vorticity advection to the east of

the upper (lower) level vorticity maximum would lead to ascending motion. Likewise, the differential vorticity advection will lead to descending motion to the west side of the low-level circulations. Thus a secondary circulation (green arrows) forms, with maximum vertical velocity near 500 hPa. With the aid of the moist process, the ascending branch of the FSC is strengthened due to condensational heating associated with enhanced convection. Therefore, the FSC is reinforced to help overcome the shear-induced drifting and "restore" the vertical alignment.
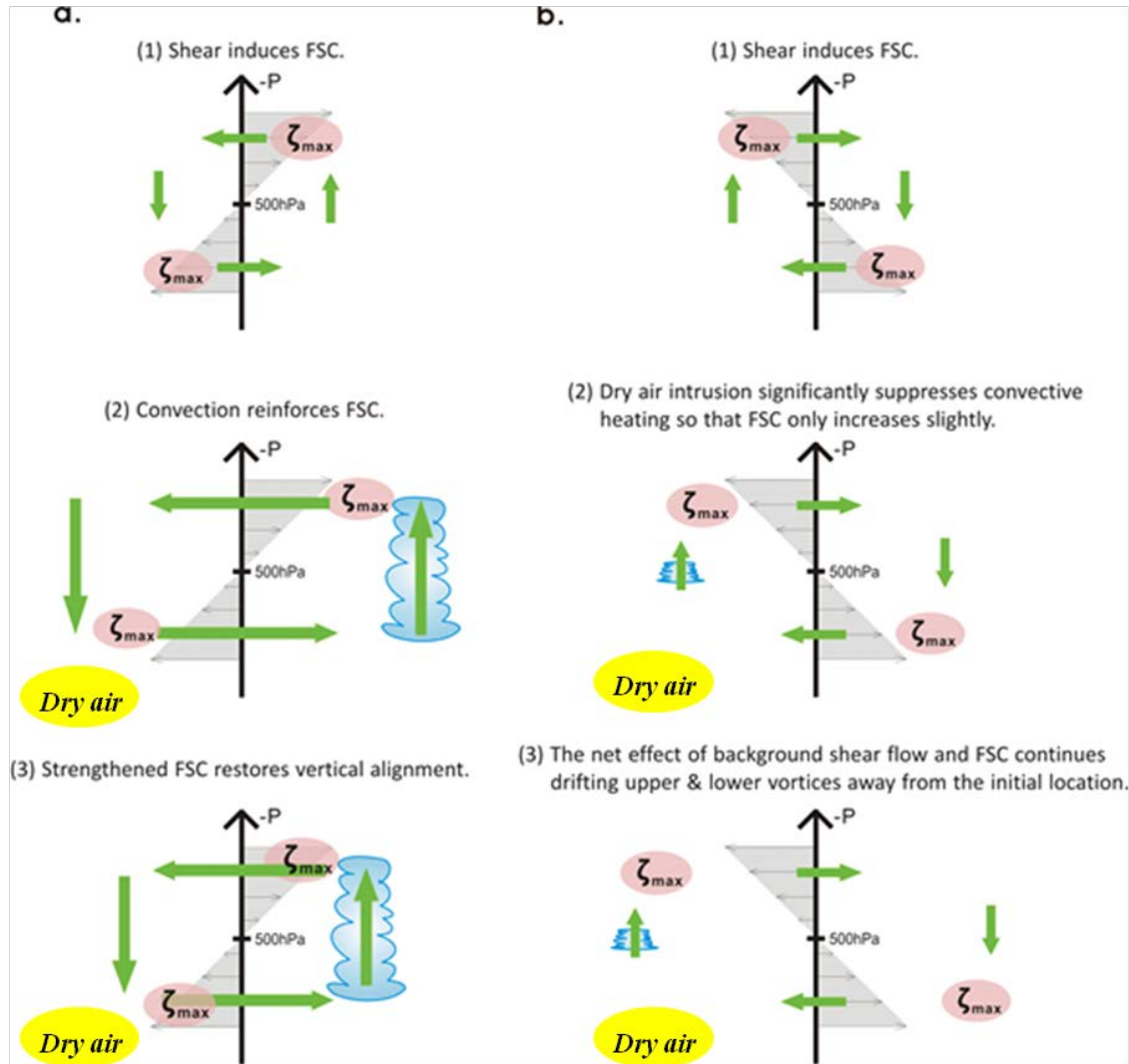

Fig. 1 Schematic summarizing the effect of FSC on the impact of vertical shear: (a) how the shear induced FSC is established and how the convection reinforced FSC helps restore the vertical alignment in WSH_DRY and (b) how the FSC fails to offset the shear advective effect due to dry air intrusion in ESH_DRY.

How does the ESH_DRY differ from the WSH_DRY? Recalled that in our model configurations, the dry air layer is place to the north of the vortex center. Due to the combination of cyclonic circulation of the vortex and the mean flow, the dry air originally located north of the vortex will be quickly advected to the west side of the circulation. As a result, there is an asymmetry of the moisture distribution in the zonal direction with dryer air to the west and moister air to the east. While the FSC for the easterly shear (upper panel in Fig. 1b) is exactly opposite to the one for the westerly shear (upper panel in Fig. 1a), the dry-air zonal asymmetric distribution comes to play in the next step. As illustrated in the middle panel of Fig. 1b for ESH_DRY, with the dryer air existing in region where the upward branch of the FSC resides, the FSC in ESH_DRY lacks convective mechanism for enhancing itself as seen in the WSH_DRY case. Therefore, the parted upper-level vortex due to the shear continues drifting away from the low-level vortex.

This study indicates the importance of dry air and vertical shear orientations in determining the impact. The background vertical shear causes the tilting of an initially vertically aligned vortex. The shear forces a secondary circulation (FSC) with ascent (descent) in the downshear (up-shear) flank. Hence, convection tends to be favored on the downshear side. The FSC reinforced by the convective heating may overcome the shear-induced drifting and "restore" the vertical alignment. When dry air is located in the downshear right quadrant of the initial vortex, the dry advection by cyclonic circulation brings the dry air to the downshear side and suppresses moist convection therein. Such a process disrupts the "restoring" mechanism associated with the FSC and thus inhibits TC development. The sensitivity experiments show that, for a fixed dry air condition, a marked difference occurs in TC development between an easterly and a westerly shear background.

4. Projected future increase in Hawaiian tropical cyclones

Possible future changes in tropical cyclone (TC) activity around the Hawaiian Islands are investigated using the state-of-the-art climate models[1–3]. We find that the future experiments (2075–2099) project a consistent and robust increase in frequency of TC occurrence around the Hawaiian Islands by about 179% compared with the simulated present-day climate (1979–2003). We apply a statistical methodology[3] to address factors responsible for the increase in TC frequency. The results reveal that the TC track change is the major factor responsible for the increased TC frequency. This implies significant future changes in large-scale flows. We find that the large-scale westward steering flows indeed increased in the subtropical central to eastern Pacific, which acts as a "pathway" leading more TCs from farther eastern Pacific toward the

Hawaiian Islands. The steering flow changes are robust regardless of models used and the assumed global warming scenarios. These results highlight possible future increase in storm-related socio-economic damage in the future in the Hawaiian Islands.

5. Changes to environmental parameters controlling TC genesis under global warming

This study uses the MRI high-resolution Atmospheric Climate Model to determine whether environmental parameters that control tropical cyclone (TC) genesis in the Western North Pacific (WNP) and North Atlantic (NA) may differ in the global warming state. A box difference index (BDI) was computed to quantitatively assess the role of environmental controlling parameters. The diagnosis of the model outputs shows that in the WNP, dynamical variables are of primary importance for separating developing and non-developing disturbances in the present-day climate, and such a relationship remains unchanged in a future warmer climate. This is in contrast to the NA, where BDI increases for all dynamic variables investigated while it shows little change for thermodynamic variables. This implies that, when compared with the present-day climate in which thermodynamic variables have a major control on TC genesis, dynamic and thermodynamic variables have equal control in the NA under the future warmer climate.

6. Effects of Monsoon Trough Intraseasonal Oscillation on Tropical Cyclogenesis over the Western North Pacific

The effects of intraseasonal oscillation (ISO) of the western North Pacific (WNP) monsoon trough on tropical cyclone (TC) formation were investigated using the Advanced Research Weather Research and Forecasting (WRF-ARW) model. A weak vortex was specified initially and inserted into the background fields containing climatologic mean anomalies associated with active and inactive phases of monsoon trough ISO.

The diagnosis of simulations showed that monsoon trough ISO can modulate TC development through both dynamic and thermodynamic processes. The dynamic impact is attributed to the lower-middle tropospheric large-scale vorticity associated with monsoon trough ISO. Interactions between a cyclonic vorticity in the lower-middle troposphere during the active ISO phase and a vortex lead to the generation of vortex-scale outflow at midlevel, which promotes the upward penetration of friction-induced ascending motion and thus upward moisture transport. In addition, the low-level convergence associated with active ISO also helps the upward moisture transport. Both processes contribute to stronger diabatic heating and thus promote a positive

convection–circulation–moisture feedback. On the other hand, the large-scale flow associated with inactive ISO suppresses upward motion near the core by inducing the midlevel inflow and the divergence forcing within the boundary layer, both inhibiting TC development. The thermodynamic impact comes from greater background specific humidity associated with active ISO that allows a stronger diabatic heating. Experiments that separated the dynamic and thermodynamic impacts of the ISO showed that the thermodynamic anomaly from active ISO contributes more to TC development, while the dynamic anomalies from inactive ISO can inhibit vortex development completely.

PUBLICATIONS

The following papers are fully or partially supported by this NRL grant:

Zuo H., T. Li, J. Liu, and M. Peng, 2016: What Controls Early or Late Onset of Tropical North Atlantic Hurricane Season? *J. Meteor. Res.*, 30 (3), 298-311, doi:10.1007/s13351-016-5119-x.

Bi, M., T. Li, M. Peng, and X.-Y. Shen, 2015: Interactions between Typhoon Megi (2010) and a Low-frequency Monsoon Gyre. *J. Atmos. Sci.*, 72 (7), 2682-2702.

Bi, M., T. Li, X. Shen, and M. Peng, 2015: To What Extent the Presence of Real-Strength Tropical Cyclones Influences the Estimation of Atmospheric Intraseasonal Oscillation Intensity?, *Atmospheric Science Letters*, 16, 438-444.

Yuan, J., T. Li, and D. Wang, 2015: Precursor synoptic-scale disturbances associated with tropical cyclogenesis in the South China Sea during 2000-2011, *International Journal of Climatology*, 35, 3454-3470.

Xu, Y., T. Li, and M. Peng, 2014: Roles of Synoptic-scale Wave Train, Intraseasonal Oscillation, and High-frequency Eddies in Genesis of Typhoon Manyi (2001). *J. Atmos. Sci.*, 71, 3706–3722.

Cao, X., T. Li, M. Peng, W. Chen, and G. Chen, 2014: Effects of the monsoon trough interannual variation on tropical cyclogenesis over the western North Pacific. *GRL*, 41 (12), 4332-4339, doi:10.1002/2014GL060307

Cao, X., T. Li, M. Peng, W. Chen, and G. Chen, 2014: Effects of monsoon trough intraseasonal oscillation on tropical cyclogenesis in the western North Pacific. *J. Atmos. Sci.*, 71, 4639-4660.

Ge, X., T. Li, and M. Peng, 2013: Tropical cyclone genesis efficiency: mid-level versus bottom vortex. *J. Tropical Meteorology*, 19(3), 197-213.

Ge, X., T. Li, and M. Peng, 2013: Effects of vertical shears and mid-level dry air on tropical cyclone developments. *Journal of the Atmospheric Sciences*, 70(12), 3859-3875.

Murakami, H., B. Wang, T. Li, and A. Kitoh, 2013: Projected future increase in tropical cyclones near Hawaii. *Nature Climate Change*, **3**, 749-754, doi:10.1038/nclimate1890.

Murakami, H., T. Li, and M. Peng, 2013: Changes to Environmental Parameters that Control Tropical Cyclone Genesis under Global Warming. *GRL*, **40** (10), 2265-2270, doi:10.1002/grl.50393.